Ultra-sensitive field sensors – An alternative to SQUIDs

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Abstract— Very low magnetic fields are detected up to now using SQUID-based devices. In the femtotesla range, only low-$T_\text{c}$ SQUIDs have a sufficiently low level of noise to measure extremely low signals, as for instance induced fields of the neural activity of the brain, for magneto-encephalography (MEG). An alternative to SQUIDs is to combine a superconducting flux-to-field transformer with a high-sensitivity giant magnetoresistive sensor (GMR).

We have fabricated and performed experiments on such an integrated YBCO-based mixed sensor. It is comprised of a GMR stack separated from a YBCO thin film by an insulating layer. The induced supercurrent in the YBCO is forced through a narrow constriction, thereby creating a local field much larger than the external field. This large local field is detected by the GMR. Effective noise levels are down to 30fT/sqrtHz, which is in the range of high-$T_\text{c}$ SQUIDs. Performance of this device is shown from liquid helium temperature (4.2 K) up to liquid nitrogen temperature (77K).

By replacing the GMR by a Tunneling Magneto Resistance (TMR) or a Colossal Magneto Resistance (CMR) sensor, and by adjusting the dimensions to optimize the local enhancement effect, the sensitivity should reach the subfemtotesla range at low frequency. A large number of applications could be investigated, from earth mapping to fundamental physics (vortex motion in superconductors, magnetic interactions...).

Index Terms— giant magnetoresistance, magnetoencephalography, magnetometers, high-temperature superconductors.

I. INTRODUCTION

Conventionally, SQUIDs are used for the detection of very low magnetic fields at low frequency for biomagnetism applications such as Magneto Encephalography (MEG). With low-$T_\text{c}$ SQUIDs sensitivities down to 1fT/sqrtHz can be achieved [1], while high-$T_\text{c}$ SQUIDs, intrinsically noisier, can achieve a sensitivity of 35fT/sqrtHz [2]. This remains too high for neural signal detection where signals are typically lower than 30fT for a frequency range from 1 to 20 Hz.

In this paper, we present an alternative magnetometer device for low frequency applications, based on the combination of a superconducting flux-to-field transformer and a Giant-Magnetoresistance (GMR) element.

In Part II, the principle of the device is developed. In Part III, we present magneto-optical imaging providing information on the performance of the device. Experimental details are given on the fabrication of YBaCuO-based devices in Part IV. Measurements and performances are given in Part V, conclusions and perspectives in Part VI.

II. DEVICE PRINCIPLE

Magneto-resistive sensors used for instance in hard disk read-heads have a high sensitivity at room temperature. For biosensor applications, the aim is to optimize a MR element with good linearity, hysteresis-free characteristic and low level of noise. Yoke-shaped sensors are good candidates since due to their shape the sensing area is free of magnetic domains, one important source of additional 1/f noise. Thermal noise of 0.4nT/sqrtHz at room temperature can be achieved by this element.

The mixed sensor principle [3] is to capture the flux related to the field to be measured by the aim of a superconducting loop, perpendicular to the applied field. A supercurrent runs in the loop to avoid magnetic field penetration and to try and keep the superconductor in the Meissner state. If this loop is locally constricted, the current density passing through the constriction will become relatively high and will locally create a high magnetic field and a high density of field lines (Fig.1). If the GMR element is placed above or below the constricted part of the loop, it will thus detect a locally enhanced field. Note that the GMR is sensitive to parallel fields, whereas the device (superconducting loop - GMR) is only sensitive to perpendicular fields.

The key point is the enhancement of the applied field, since signals in biomagnetism are much lower than the sensitivity of
the GMR itself, the enhancement must provide a factor of hundred to thousand amplification, depending on the noise signal of the MR element and the application (heart signals are for instance of the order of few pT).

Fig. 1. Schematic diagram of the superconducting loop when an external perpendicular field is applied. The supercurrent (light grey arrows) generates high density of field lines at the position of the constriction. The GMR sensor is placed immediately above or below the constriction.

The field enhancement depends on the dimensions of the loop (radius $R$ and width $w_l$) and of the constriction (width $w_c$).

In the case of complete screening by a ring-shaped superconductor, the screened flux is given by:

$$\phi = LI = -\pi R^2 \mu_0 H_a$$

with $\mu_0 H_a$ the applied field. The ring inductance is given by [4]:

$$L = \mu_0 R \left( \ln \left( \frac{8R}{w_l} \right) - \alpha \right).$$

$\alpha$ is equal to 2 in the case of a thin ring, and tends to $\frac{1}{4}$ in the case of a very broad ring.

Thus we may express the supercurrent $I$ induced by the external field as:

$$I = -\frac{\pi R H_a}{\ln \left( \frac{8R}{w_l} \right) - \alpha}.$$

And the local field at the constriction $H_c$ in a rough estimation (the exact field distribution can be computed taking into account the current distribution in the constriction [5], [6]) is given by

$$H_c = \frac{I}{2w_c} = \frac{R}{w_c} \frac{\pi}{2 \ln \left( \frac{8R}{w_l} \right) - \alpha} H_a.$$

Hence, the larger the ring, the higher the supercurrent. Moreover, the strength of the field lines around the constriction will be greater if the constriction is smaller (of course, the critical current of the superconductor cannot be exceeded).

Using this equation, with a 1cm$^2$ square loop and a 2µm-wide constriction, an enhancement factor of 3500 between the applied field and the local field is expected.

III. MAGNETO-OPTICAL INVESTIGATION

The field-enhancement of such a device can be measured by means of magneto-optical imaging. This powerful technique based on the Faraday effect, allows the visualization and measurement of the magnetic field distribution in a sample. The local magnetic field is detected using a Bi-doped yttrium iron garnet film, with a large Faraday effect, of the order of 0.06deg/mT. The magneto-optical image lock-in technique used is described elsewhere [7]. Its resolution for the perpendicular field is 0.7mT/sqrtHz, its spatial resolution is 0.5µm, with an unambiguous determination of the sign of the field.

A superconducting YBCO loop with a constriction is investigated in a perpendicular field to determine experimentally the enhancement factor at the position of the constriction, see Fig. 2.

Fig. 2. Magneto-optical imaging of a superconducting constriction in a 3mm-diameter loop, for an applied field of 1µT (top) and 20µT (bottom). Both images are obtained after a zero field cooling down to 4.2K. Only the region close to the constriction is shown. The size of the constriction is 25µm in length and 7µm in width. The gray scale bar gives the local field in µT perpendicular to the film. Note the different sign of field indicated by +/-.
The enhancement factor close to the constriction at 1µT external field, is a bit less than 250, which is in good agreement with the theoretical calculated gain of 240. For a higher external field of 20 µT (Fig. 2 - bottom), the enhancement factor is reduced to 30, due to the fact that the critical current in the constriction has been already reached.

IV. EXPERIMENTAL

A. Giant-Magnetoresistance

The GMR stack has the following composition [Si/SiO$_2$/Ta(5)/Ni$_8$Fe$_{19}$(4)/Co$_{90}$Fe$_{10}$(2.4)/Cu(2.4)/Co$_{90}$Fe$_{10}$(2.4)/Ir$_{20}$Mn$_{80}$(10)/Ta(10)] (thicknesses are given in nm). When patterned in a yoke-shape, it exhibits a MR ratio of 4% at room temperature and of 9% at 4.2K.

B. YBCO-based device

For epitaxial growth reasons, the YBCO cannot be deposited on top of the GMR. The YBCO is a commercial [8] 100nm-thick layer, grown on sapphire, with a $T_c$ of 88K. A Si$_3$N$_4$ insulating layer is sputtered on top of the YBCO, and smoothed by polishing. The GMR stack is then deposited on top of the Si$_3$N$_4$ in a third step. The sample is etched down to the substrate with a pattern containing the loop and the yoke shape. Insulation of the edges is achieved by angle-deposition of a thin (40nm) layer of Si$_3$N$_4$ on four steps. A second ion milling step is performed to etch the GMR stack remaining on the superconducting loop, except for the yoke which is protected by a photoresist layer. Contact pads are then deposited for the four point measurement.

![GMR stack schematic](image)

Fig. 3. Magnetoresistance as a function of in-plane field at room temperature.

![YBCO-based device](image)

V. MEASUREMENTS

A. Principle

The device is cooled down and measured in a liquid-helium cryostat, containing superconducting coils to generate a static bias field parallel to the substrate, as well as a small copper coil at the back of the sample holder to generate a field mimicking the biomagnetic signal which is perpendicular to the substrate and the superconducting loop. Before cooling the MR is measured to ensure that the perpendicular field does not have any effect. The GMR sensor is calibrated using in an in-plane field from room temperature down to 4.2K. In the linear part of the sensor, the slope at 4.2K is 3.11% per mT.

After cooling below $T_c$, a small perpendicular field generates a change in the MR of the sensor. By calculating the ratio between the applied field and the calibration field corresponding to the MR slope, one can determine the enhancement factor (or gain) of the system.
B. Results

The MR variation measured on the YBCO device as a function of the perpendicular applied field is given in Fig. 5. The MR ratio first linearly increases, then reaches a saturation value, which is the GMR saturation plateau. Indeed at 4.2K for the YBCO, the GMR saturates before the critical current is reached. The maximum slope variation in resistance is 310% per mT, to be compared with 3.11% per mT for the GMR calibration curve, giving an enhancement factor close to 100.

C. Noise measurements

To determine the sensitivity of this device, noise spectra are recorded for different temperatures (77K and 4.2K). At the lowest temperature, a higher current can be passed through the GMR sensor, thereby reducing the 1/f noise. Consequently, a resolution of 32fT/sqrtHz can be achieved in these conditions for this small-size device. This is comparable to the noise-level of high-T_c SQUIDS [2].

VI. Conclusion

We have fabricated high-sensitivity magnetometers based on a superconducting flux-to-field transformer and a GMR sensor. The performance of this device depends on the local enhancement of the applied field by the transformer and on the sensitivity of the sensing element. Enhancement factors of 500 have been obtained on a niobium-based device; on a smaller size YBCO-based device, sensitivity comparable with high-T_c SQUIDs is obtained (32fT/sqrtHz).

Performance can be improved by optimizing the dimensions of the superconducting loop (larger with a smaller constriction), as well as the MR material used to detect the enhanced field. In particular, TMR or CMR layers, exhibiting a higher sensitivity could be very good candidates to reach the subfemtotesla range.

REFERENCES

[8] The YBCO samples of this paper are commercial ones deposited by Theva GmbH, Germany.